

Experimental energy and exergy performance of a solar receiver for a domestic parabolic dish concentrator for teaching purposes



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ARTICLE INFO

Article history:

Received 7 August 2012

Revised 6 January 2014

Accepted 7 January 2014

Available online 28 January 2014

Keywords:

Domestic

Energy and exergy

Experimental

Parabolic dish concentrator

Solar receiver

Teaching

ABSTRACT

An experimental setup to investigate the thermal performance of a cylindrical cavity receiver for an SK-14 parabolic dish concentrator is presented in this technical note. The thermal performance is evaluated using energy and exergy analyses. The receiver exergy rates and efficiencies are found to be appreciably smaller than the receiver energy rates and efficiencies. The exergy factor parameter is also proposed for quantifying the thermal performance. The exergy factor is found to be high under conditions of high solar radiation and under high operating temperatures. The heat loss factor of the receiver is determined to be around 4.6 W/K. An optical efficiency of around 52% for parabolic dish system is determined under high solar radiation conditions. This experimental setup can be used as teaching tool for people with little or no knowledge about solar dish concentrators due to its simplicity and the basic mathematical formulations applied. Different types of receivers and different types of deep focal region parabolic dishes can also be tested with the experimental setup.

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Introduction

Solar parabolic dish concentrators are useful in providing high temperatures for different solar thermal applications which include solar cooking, solar water heating, solar thermal power and solar thermal steam generation. A parabolic dish concentrator is composed of a parabolic reflecting surface (dish) and a solar thermal receiver at the focal region of the dish. Parabolic dish concentrators generally attain much higher temperatures than the other types of solar concentrators and can be used in processes that require high temperatures. The receiver of the parabolic dish concentrator has to be well designed such that it can achieve high temperatures with minimal heat losses. Extensive theoretical and experimental works on parabolic dish concentrators for small to large industrial applications have been done in recent years (Cui et al., 2003; Li et al., 2011; Lovegrove et al., 2011; Reddy and Kumar, 2009; Shuai et al., 2008; Wang and Siddiqui, 2010; Wu et al., 2010a, 2010b; Wua et al., 2010).

In recent years, concerted efforts to study the performance of small scale domestic parabolic dish concentrators for domestic applications relevant to developing countries have been done. Kaushika and Reddy (2000) investigated a low cost solar steam generating system which incorporated an innovative receiver design for a deep parabolic dish. Their measurements indicated that the system could achieve 70–80% efficiency at a very low cost with innovative fuzzy volumetric receivers. Kumar and Reddy (2008) compared different receivers for a parabolic dish concentrator. A cavity receiver, a semi-cavity and a modified

cavity receiver were compared using numerical investigations. The researchers found out that the modified cavity receiver had the best performance due to its lower convective heat losses. Investigations of a solar cavity receiver for a dish concentrator were done by Prakash et al. (2009). Convective heat losses were found to be very high under windy conditions. The experimental analysis of a water heating experiment using a Scheffler parabolic reflector with a reflector area of 8 m² was done in India (Patil et al., 2011). The Scheffler parabolic dish reflector consists of a primary parabolic reflector which focuses solar radiation onto a secondary reflector where a solar thermal device utilising the radiation is placed. Performance analysis of the collector revealed that the average power and efficiency in terms of water boiling was 1.30 kW and 21.61% respectively against an average beam radiation of 742 W/m². A mathematical model to develop a Scheffler-type solar concentrator coupled with a Stirling engine was proposed (Ruelas et al., 2012). Results indicated that the highest concentration was obtained at an edge angle of 45°.

The design, construction and performance evaluation of a spherical solar cooker with two axis tracking was done by Abu-Malouh et al. (2011). Results indicated that a maximum temperature of around 93 °C could be achieved inside a pan placed at the focal region when the maximum ambient temperature was around 32 °C. Kumar et al. (2012) considered the second law of thermodynamics and performed an exergy based performance evaluation of four types of solar cookers which were a solar box cooker (SBC), an SK-14 parabolic dish solar cooker, a Scheffler parabolic reflector community type of cooker and a parabolic trough concentrating cooker. The SK-14, is a commercially available domestic solar cooking concentrator developed by Dr. Ing. Dieter Seifert, marketed, produced, distributed and sold by EG Solar

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(EG Solar, 2013) mostly for developing countries. Its use is widespread around India. It has a diameter of 1.4 m and the receiver is placed inside the rim of the dish.

Results obtained by Kumar et al. (2012) showed that the Scheffler community cooker and the SK-14 parabolic cooker had better performances than the other types of cookers. The thermal performance of the Scheffler community cooker was however better than that of the SK-14 parabolic cooker in terms of the exergy. A conical receiver for a paraboloidal concentrator with a large rim angle was investigated experimentally and theoretically (Hernandez et al., 2012). The conical receiver was found to be adequate for the deep parabolic dish.

An energy and exergy efficiency comparison of a community-size and a domestic-size paraboloidal solar cooker performance was done by Kaushik and Gupta (2008). The performance of the community solar cooker was found to be comparable to that of the domestic cooker. Results of a new design for fabricating solar parabolic concentrators based on flexible petals have been presented (Li and Dubowsky, 2011). The design concept was deemed to have the potential of providing precision solar parabolic solar collectors at a substantially lower cost than conventional methods. The determination of the spatial extent of the focal point of a parabolic dish reflector using a red laser diode has been done (Mlatho et al., 2010). It was suggested that the laser diode could be used in place of a radiometer in cases where the radiometer was not available.

Most of the reviewed articles are for specific types of parabolic dish concentrators with detailed mathematical derivations and analyses of heat transfer parameters only valid for the particular system. The mathematics is rather cumbersome for people with a limited mathematical scope but who are interested in the design and characterization of simple receivers for solar domestic applications. Most of the thermal performance evaluation parameters are either based on empirically determined heat transfer numbers and thermal energy performance efficiencies which do not account for irreversibilities catered for by an exergy analysis. Furthermore, the reviewed literature shows few research articles on deep parabolic dish concentrating systems with a large rim angle for simple small scale domestic applications like the SK-14 (Murty et al., 2006) parabolic solar concentrator. In deep parabolic dish concentrators the focal region is inside the rim of the parabolic reflector whereas in shallow focal region concentrators, the focal region is outside the rim of the parabolic reflector (Solar Cooking, 2013).

According to the literature reviewed, an experimental comparison of different receivers for these deep dishes has rarely been done.

In this technical note, an experimental setup to evaluate the performance of a simple laboratory fabricated cylindrical cavity receiver for a deep parabolic dish concentrator is presented. Results are presented in terms of the energetic and the exergetic performance. Simple thermal performance measures are presented which can be used for comparison purposes of different receivers for domestic parabolic dish concentrators with deep focal regions.

Experimental setup

A schematic diagram of the operation of the parabolic dish concentrator and the associated components is shown in Fig. 1. Solar radiation incident onto reflecting mirrors of a heliostat assembly is reflected to an SK-14 parabolic dish concentrator which has a cylindrical cavity receiver at its focal region. The SK-14 parabolic is placed in a hut at a garage door which is opened such that the solar radiation can be reflected from the heliostat to the dish where it is absorbed by the receiver at the focal region. The heliostat assembly is driven by two DC motors such that azimuth and elevation tracking of the sun is possible. The DC motors are currently being driven by a 10 A power supply connected to two push-button switches for manual tracking in the azimuth and elevation directions to keep the sun's radiation focused onto the receiver. Oil from a storage tank is circulated with the use of a positive displacement pump such that it enters the receiver at a lower temperature, T_{in} , absorbs solar thermal energy on the receiver and leaves at a higher temperature of T_{out} . The closed loop cycle is continued for as long as solar radiation is available. The charging pump is driven by a DC power supply.

A photograph of the hut where the parabolic dish concentrator is placed is shown in Fig. 2. The garage door when opened acts as an aperture for reflected solar radiation from the mirrors of the heliostat to the parabolic reflector. The aperture area of the door when opened is around 4 m² and solar energy is reflected from the heliostat mirrors to the 1.4 m diameter SK-14 parabolic reflector which has a receiver attached at its focal region. During periods of bad weather conditions, the garage door is closed to protect the parabolic dish reflector. The heliostat assembly is shown in Fig. 3. It consists of six mirrors which rotate on a mechanical framework in the azimuth and elevation

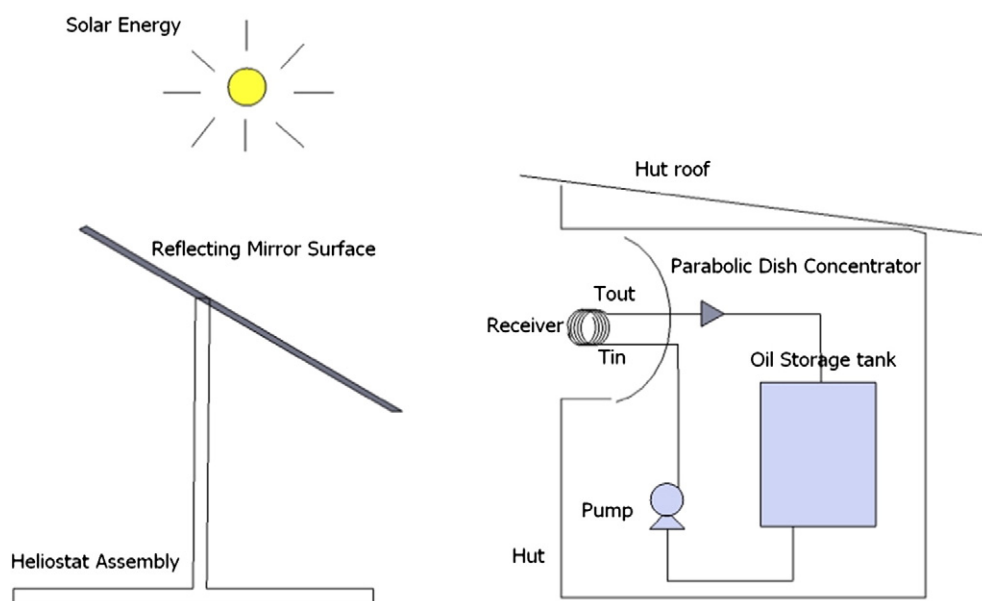


Fig. 1. Schematic of experimental setup.



Fig. 2. Hut containing experimental apparatus.

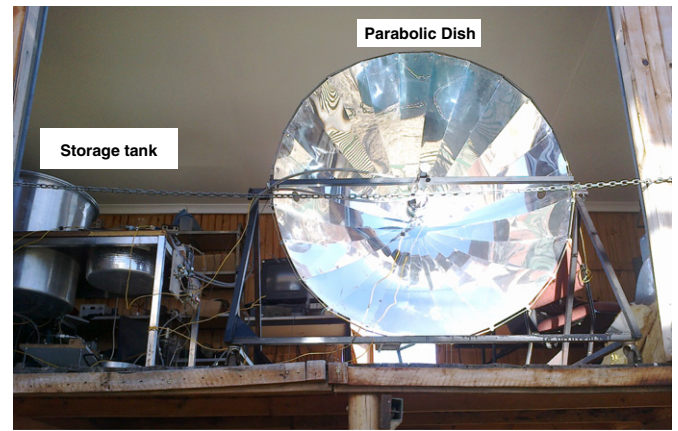


Fig. 4. An SK-14 parabolic dish concentrator at the garage door aperture connected to the storage tank.

directions as they focus solar radiation onto a receiver of an SK-14 parabolic dish concentrator. The mirrors are made of glass with a length of 1.07 m and a width of 0.37 m (resulting in mirror area of $\sim 0.396 \text{ m}^2$).

The advantage of this system is that different receivers can be tested since the parabolic dish is fixed and the heliostat is the only component that rotates to focus the solar radiation onto the receiver. Another advantage is that a different parabolic dish concentrator can also be tested with the same setup by replacing the current dish with a new one at the garage door aperture. A further advantage is that the total cost of the experimental setup is reasonably priced at around US \$12,000 ($\sim \text{R } 120,000$) which is justified by considering the fact that many experimental tests can be carried with different receivers, parabolic dish concentrators and thermal energy storage tanks. Only locally available resources in South Africa were used to build the system and no technically specialized materials were imported especially for building the heliostat. The accuracy of the heliostat tracking mechanism can be improved to get better results by automating the tracking mechanism which can be a good postgraduate project.

Fig. 4 shows a photograph of the SK-14 parabolic dish and a cylindrical test cavity receiver in operation with the associated instrumentation. The figure also shows the storage tank into which the heated oil flows thus pushing colder oil back into the receiver again. A photograph and a schematic diagram showing the dimensions of the receiver are shown in Fig. 5. It consists of a cylindrical cavity in which a copper helical coil is wound on the inside and the outside surfaces of the cylinder such that circulating oil in the coil can absorb solar radiation. The receiver is painted black to increase its absorption coefficient to solar radiation.

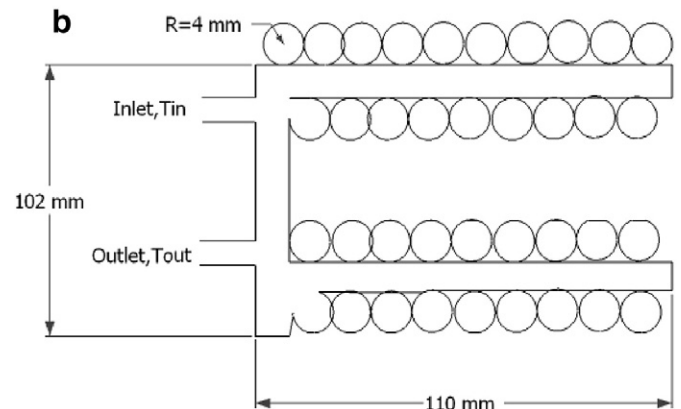


Fig. 5. Photograph (a) and (b) schematic diagrams of cylindrical cavity receiver.



Fig. 3. Heliostat assembly.

Energy and exergy analysis

Experimental energy and exergy parameters to characterize the thermal performance of the receiver are presented in this section.

Energy analysis

The useful rate of energy delivered to the circulating oil by the receiver or the receiver power depends on the flow-rate and is expressed as

$$P_R = \rho_{av} c_{av} \dot{V}_{av} [T_{Out} - T_{In}] \quad (1)$$

where ρ_{av} is the average density of the oil, which is a function of the average of T_{In} and T_{Out} , while c_{av} is the average specific heat capacity of the oil which is a function of the average of T_{Out} and T_{In} based on the Shell Thermia B (Shell S2) datasheet (Shell S2, 2011). $\dot{V}_{av}$ is the moving average flow-rate measured in ml/s. T_{In} is the colder inlet temperature of the helical coil while T_{Out} is the hotter outlet temperature of the coil after it has absorbed solar radiation. The average density is

$$\rho_{av} = -0.0006T_{av} + 0.8748 \quad (2)$$

while the average specific heat capacity is

$$c_{av} = 0.0036T_{av} + 1.8087 \quad (3)$$

where T_{av} is the average of T_{In} and T_{Out} . These functions were extrapolated from the datasheet of the heat transfer oil (Shell S2, 2011).

The receiver power is the difference between the power supplied by the solar radiation to the receiver and the overall heat losses which are assumed to be mostly convective since the receiver temperatures are not very high. The receiver power can be estimated as

$$P_R = P_S - P_L \quad (4)$$

where P_S is the solar radiation power that is reflected onto the receiver from the parabolic dish reflector. The parabolic dish reflector receives solar radiation from the heliostat mirrors that reflect the sun's solar radiation onto it. P_L is the rate of convective heat loss from the receiver. The solar radiation power onto the receiver from the parabolic dish reflector can be expressed as

$$P_S = n_{opt} A_{ap} G \quad (5)$$

where n_{opt} is the combined optical efficiency which depends on the reflectance and transmittance of the heliostat mirrors, the reflectance of the reflector material and the absorbance of the receiver. A_{ap} is the effective aperture area of the parabolic dish and G is the direct solar irradiance from the sun to the heliostat mirrors. The solar radiation is reflected by the mirrors of the heliostat to the reflecting surface of the parabolic dish concentrator which concentrates it onto a receiver placed at its focal region. G is given in (W/m^2) and is measured with an Eppley normal incidence pyrliometer (NIP) attached to an Eppley ST-1 solar tracker as already mentioned in the experimental setup. A_{ap} is actually a difference between the total reflecting area and the effective area of the receiver since the receiver tends to block part of the reflecting surface of the reflector as it casts a shadow onto the reflecting surface. For an ideal solar concentrating system $n_{opt} \approx 1$. The rate of heat loss from the receiver to the surroundings can be expressed as

$$P_L = U_L A_R (T_{av} - T_{amb}) \quad (6)$$

where U_L is the heat loss coefficient determined in $W/m^2 K$, A_R is the effective receiver area in m^2 and T_{amb} is the ambient

surrounding temperature in K. The product $U_L A_R$ in W/K is referred as to as the heat loss factor given by

$$U_L' = U_L A_R. \quad (7)$$

Substituting Eqs. (1), (5), (6) and (7) into Eq. (4) yields

$$\rho_{av} c_{av} \dot{V}_{av} [T_{Out} - T_{In}] = n_{opt} A_{ap} G - U_L' (T_{av} - T_{amb}). \quad (8)$$

The thermal energy efficiency of the receiver is defined as the ratio of rate of the energy gained by the oil to the rate of solar energy delivered by the reflecting aperture and this is expressed as

$$\eta_{th} = \frac{\rho_{av} c_{av} \dot{V}_{av} [T_{Out} - T_{In}]}{A_{ap} G}. \quad (9)$$

Dividing Eq. (8) throughout by $A_{ap} G$ yields

$$\eta_{th} = n_{opt} - \frac{U_L' (T_{av} - T_{amb})}{A_{ap} G} \quad (10)$$

which is the design equation of the solar parabolic dish concentrator used to estimate the thermal energy efficiency and the heat losses from the receiver.

Exergy analysis

The receiver exergy rate or the quality of energy delivered to the circulating fluid with reference to the surroundings can be expressed as (MacPhee and Dincer, 2009)

$$Ex_R = P_R - \rho_{av} c_{av} \dot{V}_{av} T_{amb} \ln \left(\frac{T_{Out}}{T_{In}} \right) \quad (11)$$

where all the temperatures are expressed in Kelvin. Eq. (11) can be further expressed as

$$Ex_R = \rho_{av} c_{av} \dot{V}_{av} \left([T_{Out} - T_{In}] - T_{amb} \ln \left(\frac{T_{Out}}{T_{In}} \right) \right). \quad (12)$$

The rate of solar exergy delivery by the sun to the heliostat and then to the concentrator (parabolic reflector and receiver) is given by the Petela expression (Petela, 2003) and is expressed as

$$Ex_S = G A_{ap} \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right] \quad (13)$$

where T_S is the surface temperature of the sun which can be estimated to be 5762 K. The exergy efficiency is defined as the ratio of the receiver exergy rate to the rate of solar exergy delivery and is expressed as

$$\eta_{thex} = \frac{Ex_R}{Ex_S} = \frac{\rho_{av} c_{av} \dot{V}_{av} \left([T_{Out} - T_{In}] - T_{amb} \ln \left(\frac{T_{Out}}{T_{In}} \right) \right)}{G A_{ap} \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_S} \right)^4 - \frac{4T_{amb}}{3T_S} \right]}. \quad (14)$$

The exergy factor is defined as the ratio of the receiver exergy rate to the receiver energy rate and is expressed as

$$Ex_f = \frac{Ex_R}{P_R} = \frac{\rho_{av} c_{av} \dot{V}_{av} \left([T_{Out} - T_{In}] - T_{amb} \ln \left(\frac{T_{Out}}{T_{In}} \right) \right)}{\rho_{av} c_{av} \dot{V}_{av} [T_{Out} - T_{In}]}. \quad (15)$$

Uncertainty analysis

An uncertainty analysis is performed on the receiver power P_R and the receiver exergy rate Ex_R which are the most important derived

quantities from the measurements using the propagation of error method described by Moffat (1988). For the receiver power the uncertainty is expressed as

$$\delta P_R = \sqrt{\left(\frac{\partial P_R}{\partial \rho_{av}}\right)^2 (\delta \rho_{av})^2 + \left(\frac{\partial P_R}{\partial c_{av}}\right)^2 (\delta c_{av})^2 + \left(\frac{\partial P_R}{\partial \dot{V}_{av}}\right)^2 (\delta \dot{V}_{av})^2 + \left(\frac{\partial P_R}{\partial T_{Out}}\right)^2 (\delta T_{Out})^2 + \left(\frac{\partial P_R}{\partial T_{In}}\right)^2 (\delta T_{In})^2} \quad (16)$$

while the uncertainty in the receiver exergy rate is

$$\delta P_R = \sqrt{\left(\frac{\partial P_R}{\partial \rho_{av}}\right)^2 (\delta \rho_{av})^2 + \left(\frac{\partial P_R}{\partial c_{av}}\right)^2 (\delta c_{av})^2 + \left(\frac{\partial P_R}{\partial \dot{V}_{av}}\right)^2 (\delta \dot{V}_{av})^2 + \left(\frac{\partial P_R}{\partial T_{Out}}\right)^2 (\delta T_{Out})^2 + \left(\frac{\partial P_R}{\partial T_{In}}\right)^2 (\delta T_{In})^2 + \left(\frac{\partial P_R}{\partial T_{amb}}\right)^2 (\delta T_{amb})^2} \quad (17)$$

where $\partial \rho_{av} = \pm 0.069 \text{ g/cm}^3$ and $\partial c_{av} = \pm 0.021 \text{ J/g K}$ as determined in our previous paper (Mawire et al., 2010) $\partial \dot{V}_{av} = \pm \text{dv} = \pm 1\%$ as determined from the datasheet of the flow-meter and the uncertainties in the temperature readings are taken to be $\pm 0.1^\circ \text{C}$ as determined from the accuracy of the data-logger. The maximum experimental values for receiver power and the exergy rate were determined to be around 325 W and 50 W respectively. The maximum receiver power and the exergy rate with their uncertainties were determined to be $(325 \pm 16) \text{ W}$ and $(50 \pm 3) \text{ W}$ respectively yielding reasonably low percentage uncertainties of $\pm 5\%$ and $\pm 6\%$ respectively.

Results and discussion

The solar irradiance, the receiver inlet and outlet temperatures and the ambient temperature on 8 March 2012 are shown in plot (a) of Fig. 6. The solar irradiance is almost constant at around 900 W/m^2 from the start of the experiment at $\sim 10:20 \text{ h}$ to around $12:08 \text{ h}$. Due to a passing cloud, the solar irradiance falls to very low values between $12:08 \text{ h}$ and $12:15 \text{ h}$. T_{Out} is seen to rise gradually oscillating up and down to attain a maximum value of around 160°C at around $11:40 \text{ h}$. This oscillatory behaviour is possibly due to manual tracking of the heliostat and passing light breezes of wind. During manual tracking, the mirrors on the heliostat are moved slightly in the azimuth direction using a push button switch that is connected to a DC power supply that drives the azimuth motor so that the solar radiation is refocused on to the receiver of the parabolic dish reflector when the outlet temperature of the receiver falls. An automatic heliostat control was deemed not necessary for the experiment to reduce the simplicity of the system since this was a basic test of the system. Manual tracking also allows the system to be used as an educational tool where students can manually adjust the mirrors to refocus the solar beam radiation onto the receiver when the solar beam radiation becomes defocused from the receiver. A temperature control system can be implemented to keep either the inlet temperature or the outlet temperature constant during the experiment at a variable flow-rate. This was not done due to budget constraints, time constraints and to keep the system simple. The outlet temperature also drops between $12:08 \text{ h}$ and $12:15 \text{ h}$ due to the drop in the solar radiation. The inlet temperature rises gradually with moderate oscillations to a peak of around 50°C at $12:08 \text{ h}$. The ambient is close to 30°C for most of the experiment.

Plot (b) of Fig. 6 shows the average flow-rate, the receiver power and the receiver exergy rate. The average flow-rate is seen to rise to a peak of close to 1.6 ml/s at $10:45 \text{ h}$ after which it drops to be close to 1.4 ml/s at the end of the experiment. The receiver power varies in a similar manner to the receiver outlet temperature and it can be concluded that the outlet temperature influences the receiver power to a greater extent than the other parameters. The exergy rate during the experiment is much lower than the energy rate with its maximum value being only

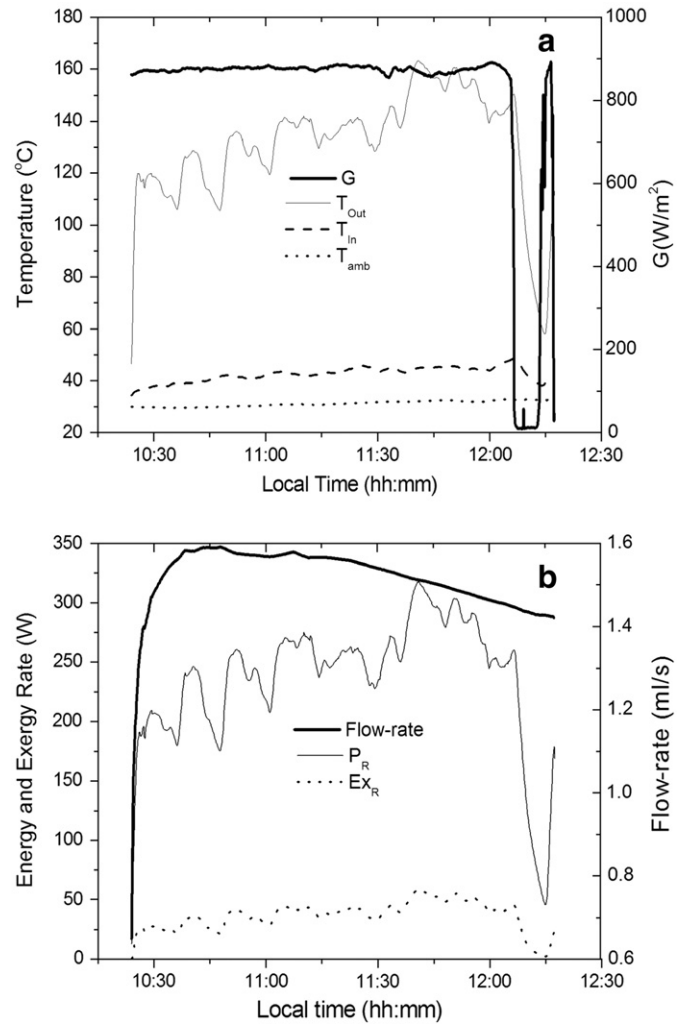


Fig. 6. (a) Solar irradiance, receiver temperatures and the ambient temperature plots on 8 March 2012. (b) Corresponding average flow-rate, receiver power and receiver exergy rate plots on 8 March 2012.

around $(50 \pm 3) \text{ W}$ as opposed to around $(325 \pm 16) \text{ W}$ for the energy rate. It can be concluded that the quality of energy from the receiver is very low possibly due to a combination of a large amount of irreversible energy changes such as heat losses and the transfer of high quality radiative energy to a fluid circulating at a relatively low temperature.

The energy efficiency, the exergy efficiency and the exergy factor variation during the experiment are shown in plot (a) of Fig. 7. Energy efficiencies, exergy efficiencies and exergy factors vary in a similar manner to the outlet receiver temperature and thus it can be concluded that it is the most predominant parameter determining these parameters. Exergy efficiencies are much lower than energy efficiencies with the maximum energy efficiency being around 0.4 and the maximum exergy efficiency being around 0.08 before the drop in the solar radiation shown in Fig. 6(a) and this suggests low quality energy obtained from the receiver.

When the solar irradiance is low, efficiencies are not evaluated and set to zero. Instantaneous variations in the value of the solar radiation from high to low values caused by passing clouds would result in very high efficiencies that are greater than unity. This is because the denominators of Eq. (9) and Eq. (14) become very small and this would be compared with the energy change of the circulating fluid thus causing the efficiencies greater than unity. This is the reason why the efficiencies are set to zero and not evaluated from $12:08 \text{ h}$ to $12:15 \text{ h}$ in plot (a) of Fig. 7. On the other-hand, the exergy factor is lower than the energy efficiency peaking to around 0.18 at high solar radiation conditions and

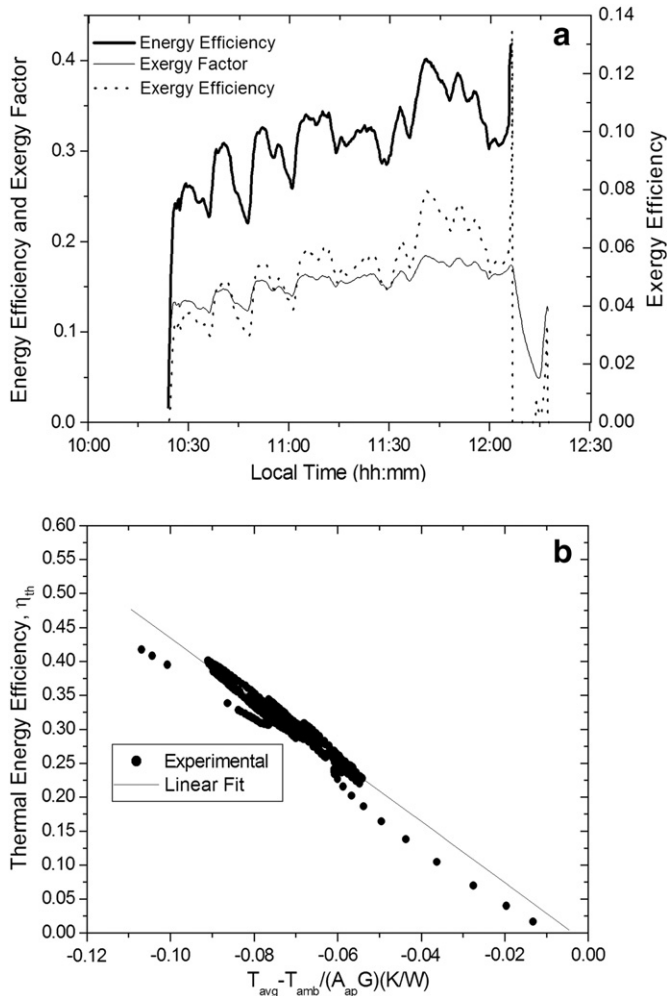


Fig. 7. (a) Energy efficiency, exergy efficiency and exergy factor plots on 8 March 2012. (b) Thermal energy efficiency as a function of the difference between the average temperature and the ambient temperature on 8 March 2012.

falling to around 0.05 when the solar radiation is low. The exergy factor can also be used as a measure of the performance of the receiver. The exergy factor appears to be relatively high under high solar radiation conditions when the outlet temperature is high and it falls when the solar radiation is low.

Plot (b) of Fig. 7 shows experimental results and linear fit of the thermal efficiency as a function of the difference between the average temperature and the ambient temperature. The linear fit produces a gradient of $\sim(4.50 \pm 0.04)$ W/K as the heat loss factor which implies that heat losses are high. Heat losses are high possibly due to solar radiation absorbed from all the surfaces of the cylindrical receiver with a greater surface area than the other receivers reported in literature (Hernandez et al., 2012; Jilte et al., 2013). More work is to be carried out with different experimental receivers to find the optimal shape to reduce heat losses. Eq. (10) predicts a straight line graph with an intercept of n_{opt} (the optical efficiency). The intercept of the line can be estimated to be around 0.52 and this implies an optical efficiency of 52% for the parabolic dish concentrator. This efficiency is greater than the optical efficiency of a recently reported dish with a large rim angle (Hernandez et al., 2012). Fluctuations below the linear fit are most probably due to experimental uncertainties and fluctuations in the receiver outlet temperatures at lower solar radiation conditions which affect evaluation of the energy efficiency.

Fig. 8 shows the exergy factor plotted as function of the temperature difference between the outlet and inlet temperatures of the receiver with a linear fit of the data. As the temperature difference increases,

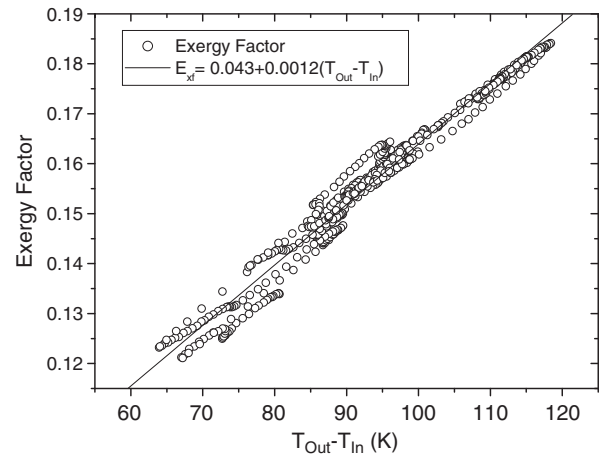


Fig. 8. Exergy factor as function of $T_{out} - T_{in}$ on 8 March 2012.

the exergy factor also increases suggesting that greater exergy is obtained when the temperature difference is high and this occurs when the outlet temperature is high and when the solar radiation is high. The graph also shows that the temperature difference has to be greater than or equal to 90 K for the exergy factor to be greater than or equal to 0.15.

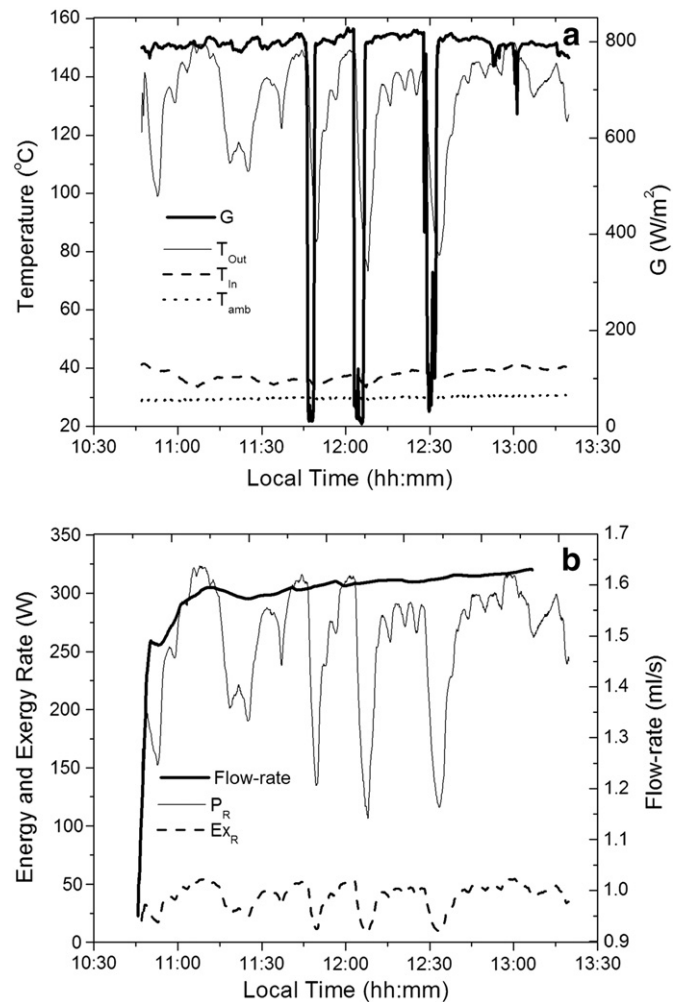


Fig. 9. (a) Solar irradiance, receiver temperatures and the ambient temperature plots on 20 March 2012. (b) Corresponding average flow-rate, receiver power and receiver exergy rate plots on 20 March 2012.

The plots of Fig. 9(a) show the solar irradiance, the receiver temperatures and the ambient temperature under some instances of cloud cover on 20 March 2012. Passing clouds caused the solar irradiance to fall to very low values at around 11:30 h, 12:07 h and 12:30 h. The average solar radiation was around 800 W m^{-2} for most of the experimental period. Evident drops in the outlet temperature at periods of low solar radiation are shown in Fig. 9(a). The maximum value of the receiver outlet temperature is around 150°C which is lower than that depicted in plot (a) of Fig. 6 due to the lower amount of solar radiation. Plot (b) of Fig. 9 shows the flow-rate gradually rising to become around 1.63 ml/s at the end of the experiment as compared to the gradual drop of the flow-rate depicted in Fig. 6(b). The receiver power is much greater than the receiver exergy rates and the maximum values are comparable to those depicted in Fig. 6(b).

Efficiencies depicted in Fig. 10(a) show a dependence on the outlet temperature of the receiver. The energy efficiency is greater than the exergy efficiency. At low solar radiation conditions the efficiencies cannot be evaluated as explained in the plots of the efficiencies in Fig. 7(a). Efficiencies depicted in plot (a) of Fig. 10 are comparable to those depicted in plot (a) of Fig. 7. The exergy factor is also seen to drop at low solar radiation conditions and thus it can be used as a thermal performance parameter. When comparing the energy efficiency of our experimental SK-14 parabolic concentrator with a modified receiver to that of a typical solar cooking application presented by Chandak et al. (2011) we find that their overall thermal efficiency is about 59% and

our results yield a maximum thermal energy efficiency of 45%. Our experimental values are lower possibly due to the non-optimised shape of the receiver which results in more heat losses. Our maximum energy and exergy efficiencies are found to be around 45% and 10% respectively. The energy efficiency is comparable to the one reported by Kaushik and Gupta (2008) of 43.56% for an SK-14 solar parabolic dish cooker with 5 kg of water in a non circulating mode. Our maximum exergy efficiency of 10% is greater than that reported by Kaushik and Gupta of 2.72%. This is possibly due to the lower operating water temperature reported by Kaushik and Gupta which varied from 23°C to 96°C whereas the average of the inlet and outlet temperatures varied between 43°C and 110°C in our study. We cannot definitely conclude that our experimental setup results in a greater exergy efficiency since our mode of operation is different. Our mode of operation is through circulating a fluid while the other authors used a fixed amount of non-circulating fluid.

The linear fit of the experimental data of Fig. 10(b) produces a heat loss factor of $(4.70 \pm 0.05) \text{ W/K}$ which is comparable to that of Fig. 7(b). However, due to fluctuations in the solar radiation which result in unrealistic high efficiencies, the optical efficiency appears to quite high at 0.8. The data in Fig. 10(b) are more scattered than in Fig. 7(b) due to the solar irradiance fluctuations. It can be included that the optical efficiency determination is not very valid when the solar radiation fluctuates. The average value of the heat loss factor is found to be about 4.6 W/K .

Conclusion

An experimental setup to investigate the thermal performance of a cylindrical cavity receiver for an SK-14 parabolic dish concentrator has been done using energy and exergy analyses. The receiver exergy rates and efficiencies were found to be smaller than the receiver energy rates and efficiencies. At lower solar radiation conditions efficiencies were not calculated due to stored energy in the receiver which would result in high efficiencies under low solar radiation conditions. The exergy factor parameter was also evaluated to determine the thermal performance of the receiver. The exergy factor parameter was found to be high under conditions of high solar radiation and higher receiver operating temperatures. The heat loss factor was also determined to be around 4.6 W/K . An optical efficiency of around 52% was determined under high solar radiation conditions. This experimental setup can act as a teaching tool to people with little or no knowledge about solar dish concentrators due to its simplicity and the basic mathematical formulations done. Different type of receivers and different types of deep focal region parabolic dishes can also be tested with the experimental setup. The experimental setup can also be used for domestic solar thermal applications like indoor solar cooking and indoor solar water heating.

Nomenclature

A_{ap}	Effective aperture area of dish m^2
A_R	Effective receiver area m^2
c_{av}	Average specific heat capacity of oil $\text{J kg}^{-1} \text{K}^{-1}$
G	Solar irradiance W m^{-2}
Ex_f	Exergy factor –
Ex_R	Receiver exergy rate W
Ex_S	Rate of solar exergy delivery W
P_L	Rate of convective heat loss W
P_R	Receiver power W
P_S	Solar radiation power W
T	Temperature K
T_{amb}	Ambient temperature K
T_{av}	Average temperature K
T_{in}	Inlet receiver temperature K
T_{out}	Outlet receiver temperature K
T_s	Surface temperature of the sun K

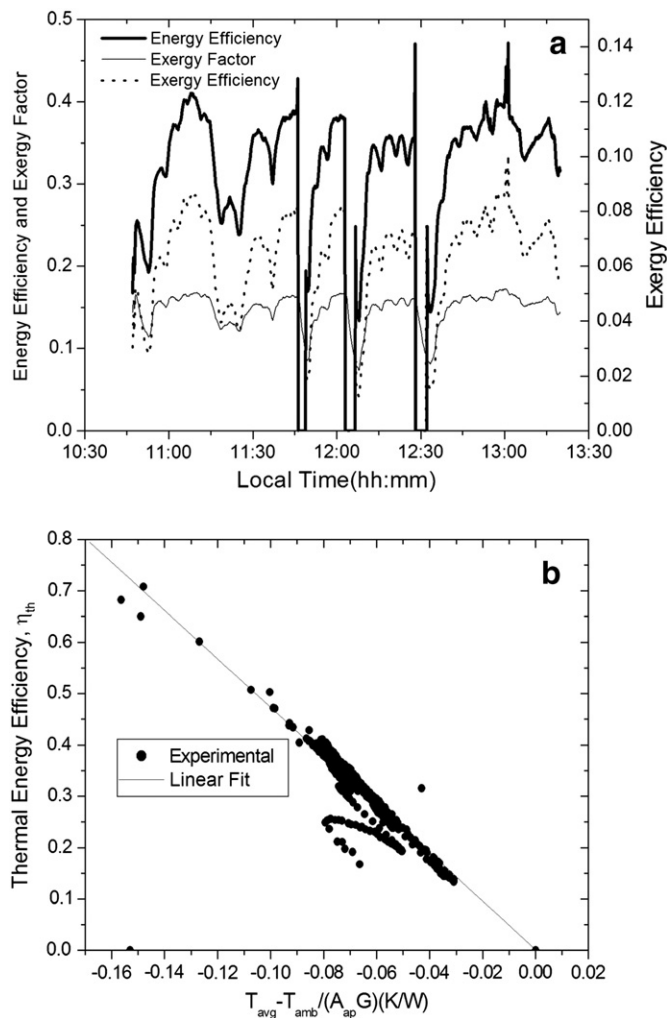


Fig. 10. (a) Energy efficiency, exergy efficiency and exergy factor plots on 20 March 2012. (b) Thermal energy efficiency as a function of the difference between the average temperature and the ambient temperature on 20 March 2012.

U_L	Heat loss coefficient $W\ m^{-2}\ K^{-1}$
U_L'	Heat loss factor $W\ K^{-1}$
$\dot{V}_{av}$	Average flow-rate ml/s
ρ_{av}	Average density of oil $kg\ m^{-3}$
n_{opt}	Optical efficiency –
η_{th}	Energy efficiency –
η_{thex}	Exergy efficiency –

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